Status of the MUonE experiment

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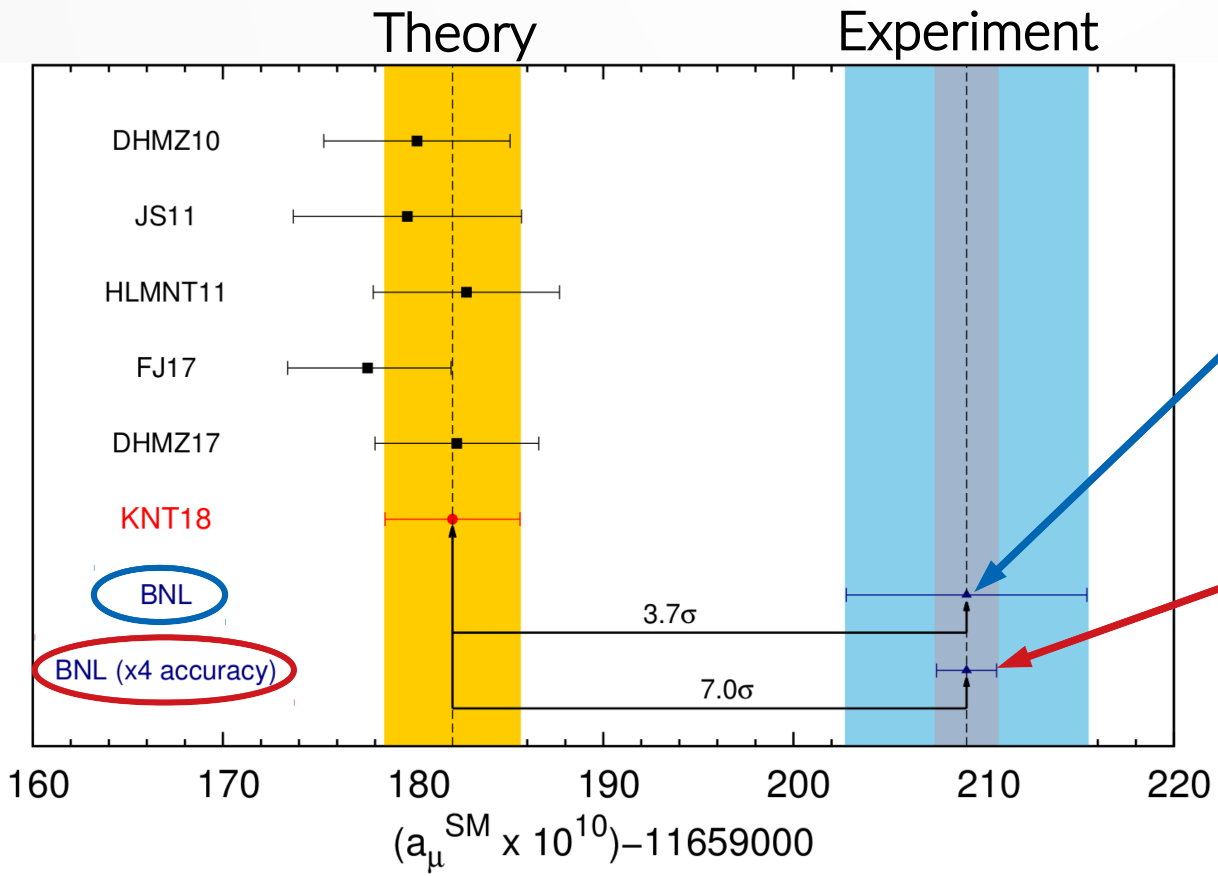
Outline

- The muon g-2 and the hadronic contribution
- The MUonE experimental proposal
- Test Run 2021
- Conclusions

The muon g-2

Muon magnetic anomaly can be both measured and computed with very high precision, providing a stringent test of the Standard Model.

$$a_\mu = \frac{g_\mu - 2}{2}$$



Latest measurement of a_μ

Accuracy: 540 ppb
3.7σ discrepancy between theory and experiment

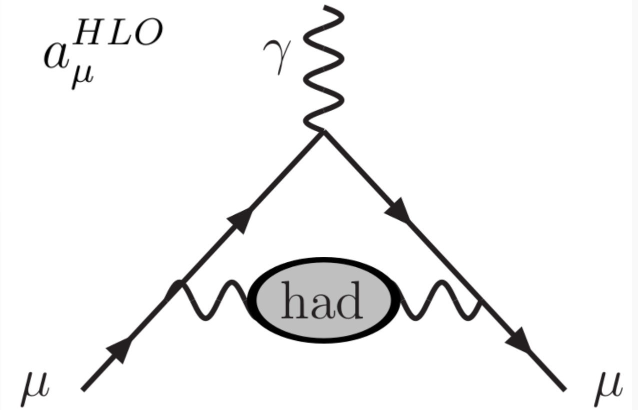
New experiment currently ongoing at Fermilab.

Aimed accuracy: 140 ppb

7σ if experimental value is confirmed.

Calculation of a_μ in the Standard Model

$$a_\mu^{SM} = a_\mu^{QED} + a_\mu^{EW} + a_\mu^{had}$$



Calculated using perturbation theory

$$a_\mu^{QED} \sim 10^{-3}$$
$$\delta a_\mu^{QED} \sim 10^{-12}$$

$$a_\mu^{EW} \sim 15 \cdot 10^{-10}$$
$$\delta a_\mu^{EW} \sim 10^{-11}$$

Main contribution to the theoretical error

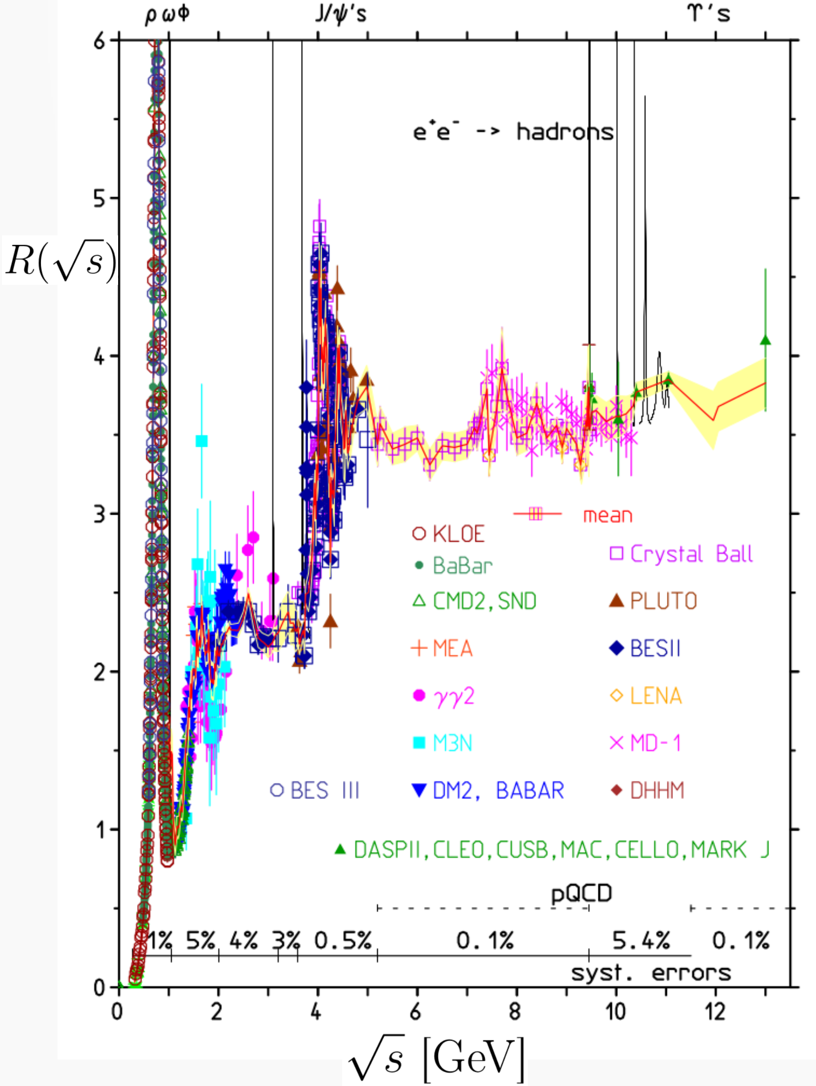
$$a_\mu^{HLO} = (693.1 \pm 4.0) \times 10^{-10}$$

Phys. Rep. 887 (2020), 1

Perturbation theory cannot be used for the hadronic contribution
(QCD is non perturbative at low energies)

The determination of a_μ^{HLO} needs to rely on experimental data

The hadronic contribution a_μ^{HLO} : time-like approach



Dispersion relation:

$$a_\mu^{HLO} = \frac{\alpha_0^2}{3\pi^2} \int_{4m_\pi^2}^{\infty} ds \frac{K(s)}{s} R(s)$$

$$R(s) = \frac{\sigma(e^+e^- \to \text{hadrons})}{\sigma(e^+e^- \to \mu^+\mu^-)}$$

$K(s) \sim 1/s$ smooth function

Measured at e^+e^- accelerators

- Large fluctuations at low energies
- Merge measurements from different experiments
- Large systematic error

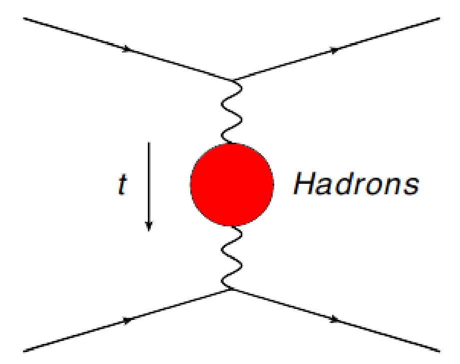
$$\delta a_\mu^{HLO} \sim 4 \cdot 10^{-10} \quad (\sim 0.6\%)$$

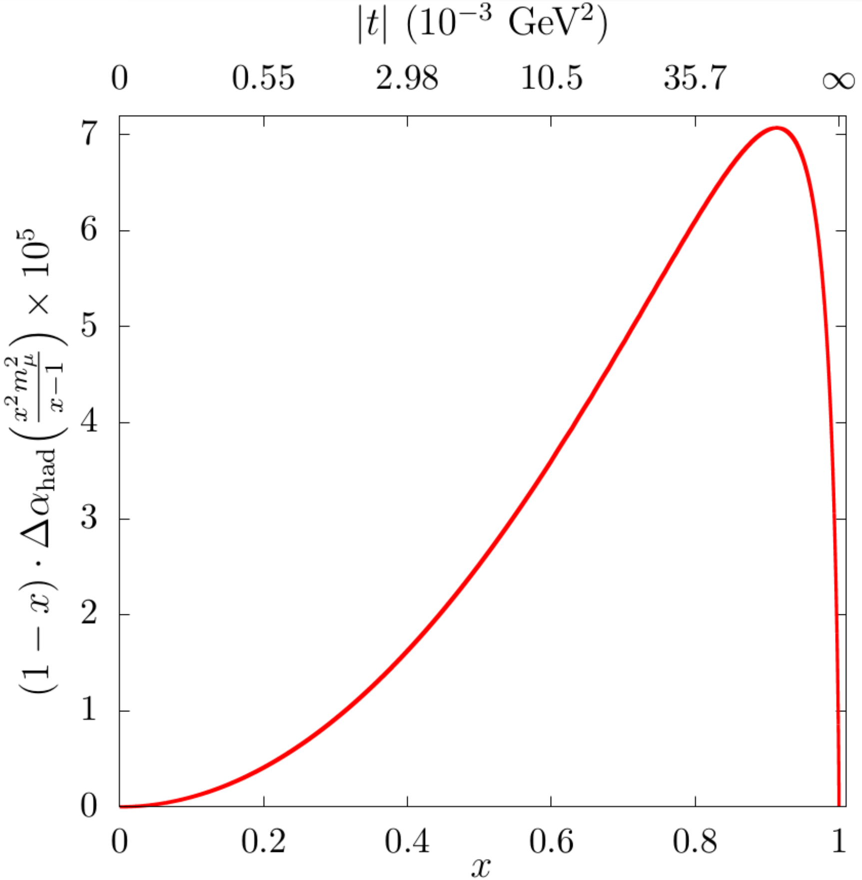
The hadronic contribution a_μ^{HLO} : space-like approach

This method is completely independent from the time-like approach

$$a_\mu^{HLO} = \frac{\alpha_0}{\pi} \int_0^1 dx(1-x)\Delta\alpha_{had}[t(x)]$$

$$t(x) = \frac{x^2 m_\mu^2}{x-1} < 0$$





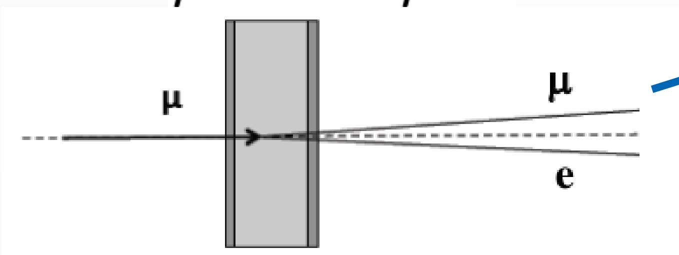
Based on the measurement of $\Delta\alpha_{had}(t)$: hadronic contribution to the running of the electromagnetic coupling constant

Phys. Lett. B 746 (2015), 325

The MUonE experiment

Extraction of $\Delta\alpha_{had}(t)$ from the differential cross section of the interaction

$$\mu\ e \rightarrow \mu\ e$$

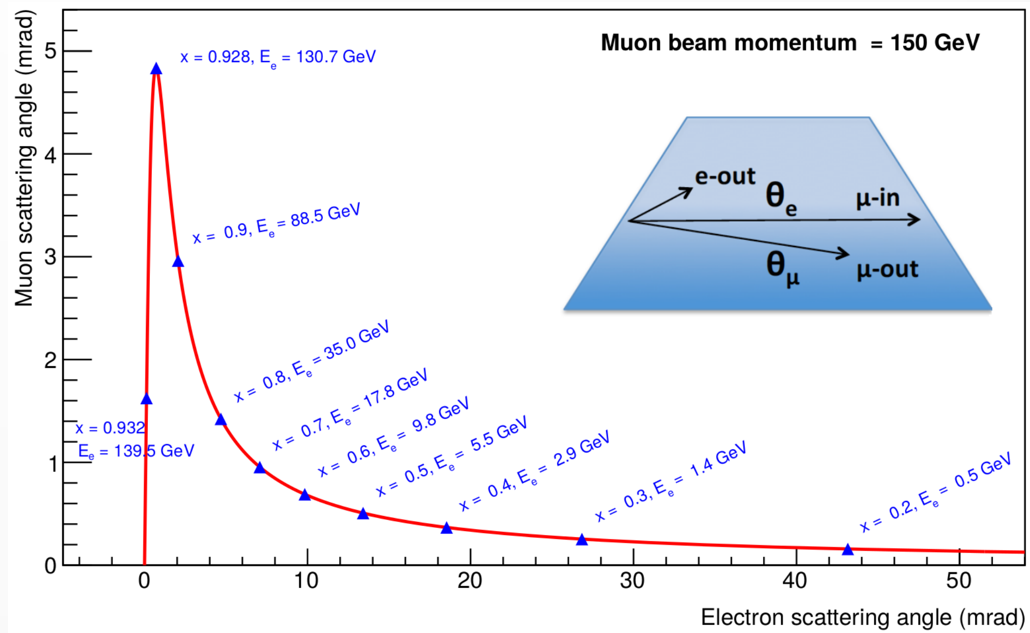


$$\frac{d\sigma_{data}/dt}{d\sigma_{MC}^{no\ VP}/dt} = \frac{1}{|1 - \Delta\alpha_{lep}(t) - \Delta\alpha_{had}(t)|^2}$$

From theoretical calculation

To be measured

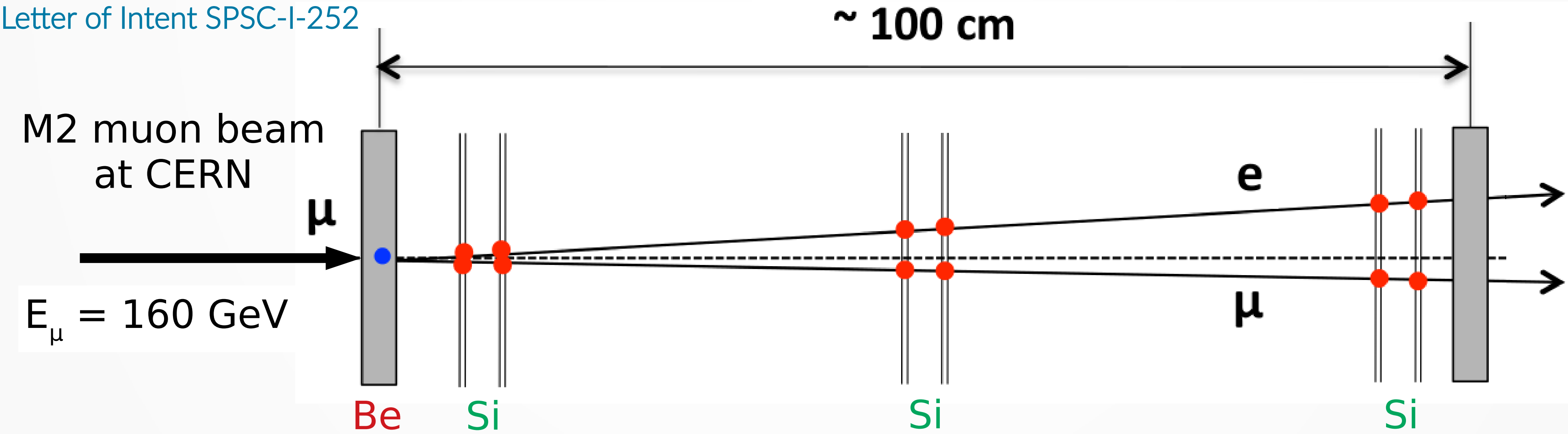
- A beam of 160 GeV muons allows to cover 87% of the a_μ^{HLO} integral
- Correlation between muon and electron angles allows to select elastic events and reject background (e^+e^- pair production)
- Boosted kinematics: θ_μ < 5 mrad, θ_e < 50 mrad



Eur. Phys. J. C 77.3 (2017), 139

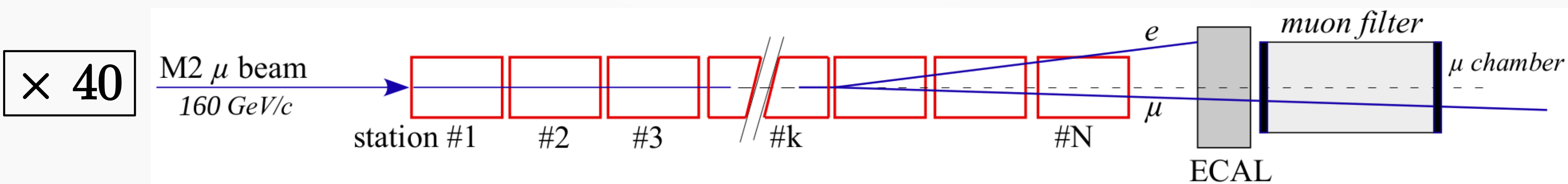
The experimental apparatus

Letter of Intent SPSC-I-252



Beryllium target
1.5 cm thickness

Tracking system: 3 pairs of
silicon strip detectors



Achievable accuracy

40 stations + 3 years of data taking = **Statistical accuracy on a_μ^{HLO}: 0.3%**

Competitive with the latest time-like accuracy

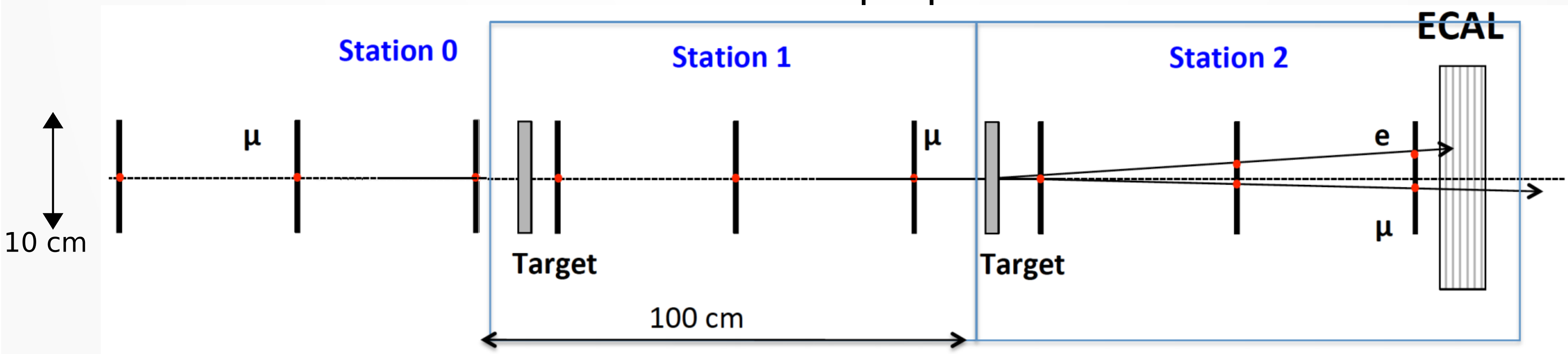
The big challenge of the experiment is to reach a comparable systematic accuracy

Systematic uncertainty of 10 ppm at the peak of the integrand function

- Longitudinal alignment (~10 μm)
- Knowledge of the beam energy (few MeV)
- Multiple scattering (~1%)

Test Run: 3 weeks in Fall 2021

A Test Run with a reduced detector has been approved by SPSC, to validate our proposal.



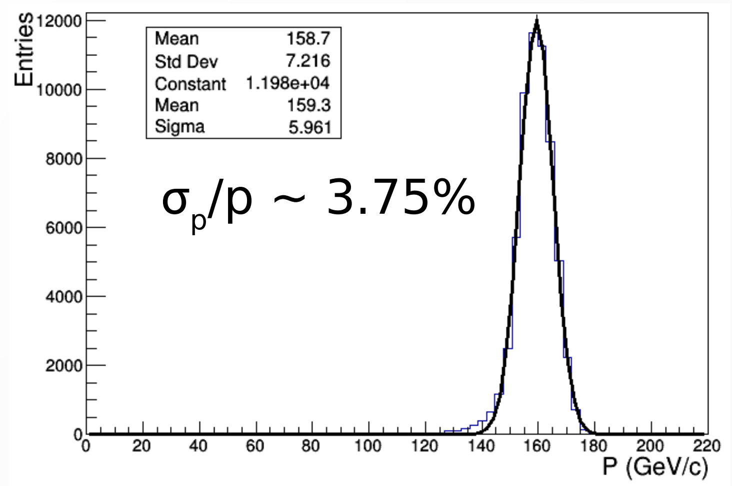
Main goals:

- Pretracker +
- 2 MUonE stations +
- ECAL

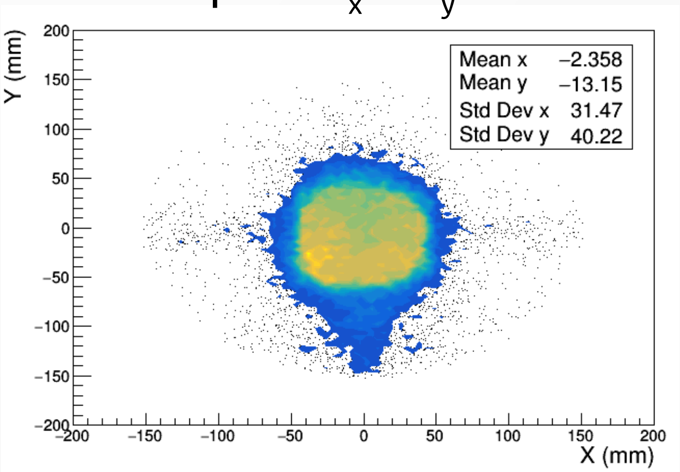
- Confirm the system engineering.
- Monitor mechanical and thermal stability.
- Assess the detector counting rate capability.
- Check the DAQ system.
- Take data to extract $\Delta\alpha_{\mathrm{lep}}(t)$.

Location: M2 beam line at CERN

Beam momentum



Beam spot: $\sigma_x \sim \sigma_y \sim 2.7$ cm



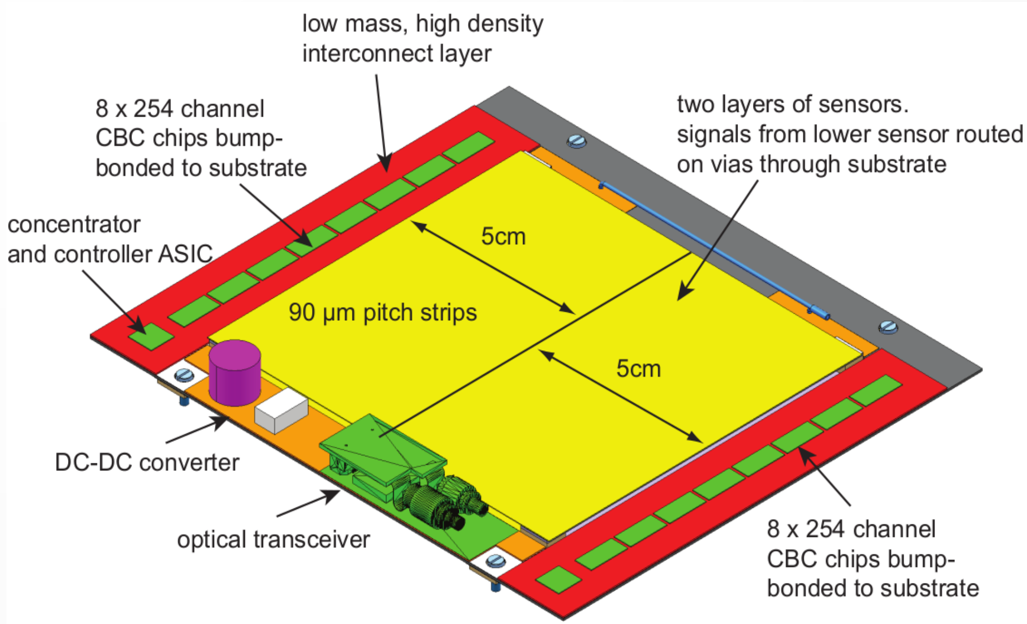
- Location: upstream the COMPASS detector (CERN North Area)
- Low divergence muon beam: $\sigma_{x'} \sim \sigma_{y'} \sim 0.3$ mrad
- Maximum rate: 50 MHz
- Spill duration ~ 5 s. Duty cycle ~ 25%

Tracker: CMS 2S modules

Silicon strip sensors currently in production for the CMS-Phase2 upgrade

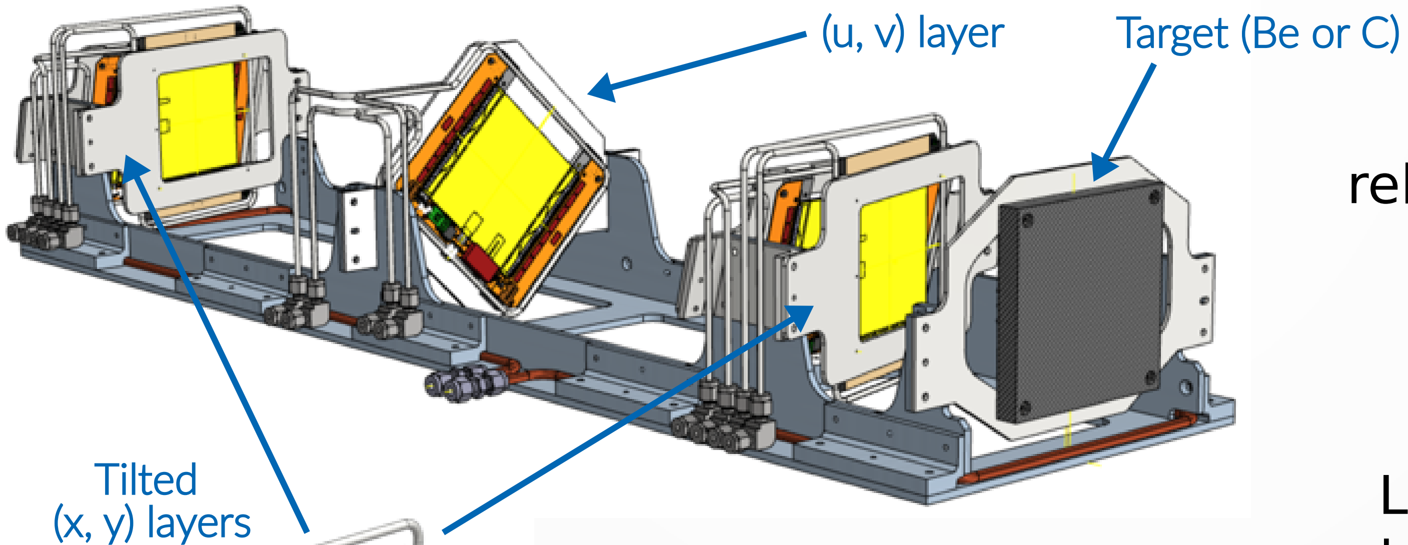
Two close-by strip sensors reading the same coordinate.

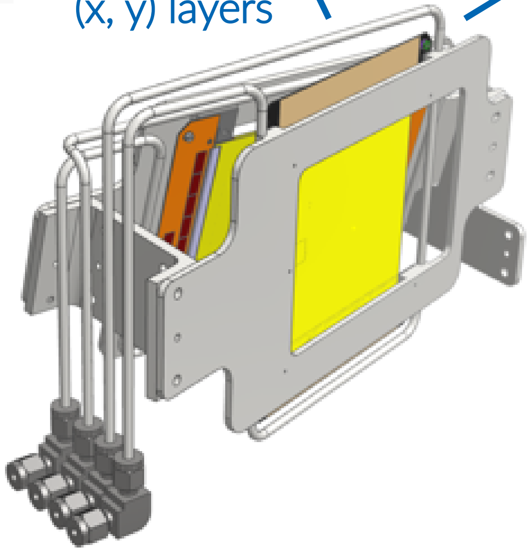
This provides background suppression from single-sensor hits and rejection of large angle tracks.



- Thickness: $2 \times 320\ \mu m$
- Pitch: $90\ \mu m \rightarrow \sigma_x \sim 26\ \mu m$
- Readout rate: $40\ MHz$
- Area: $10\ cm \times 10\ cm$ → Full angular acceptance with one module

Tracking station





Stringent request: relative position within a station must be stable at 10 μm.

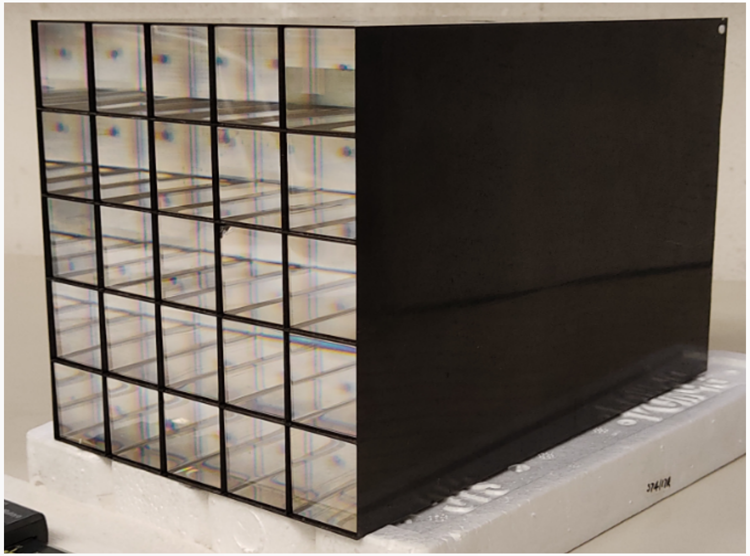
↓

Low CTE mechanical structure: INVAR (alloy of 65%Fe, 35%Ni).

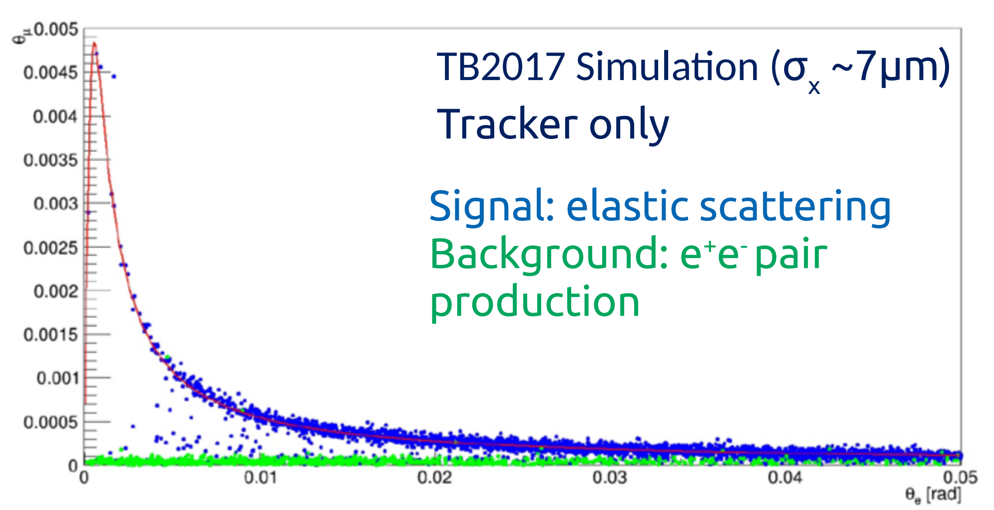
- (x, y) layers tilted by 233 mrad, to improve single hit resolution.
  - Simulation studies show a resolution of ~10 μm.
- (u, v) layers to solve reconstruction ambiguities.

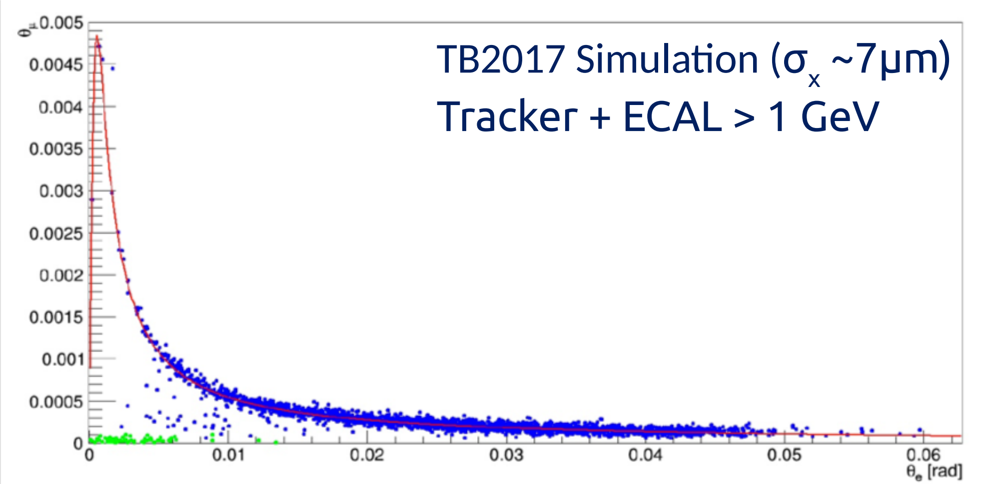
ECAL

Needed for particle ID and background rejection.

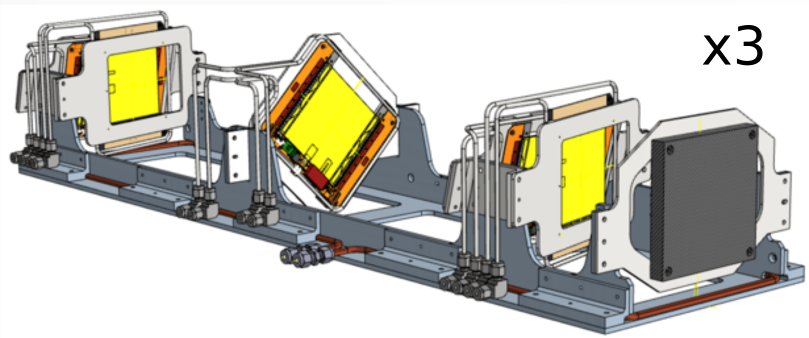


- 5x5 $PbWO_4$ crystals (CMS ECAL).
- 2.85x2.85 cm^2
- Total area: ~14x14 cm^2
- Readout: APD sensors.





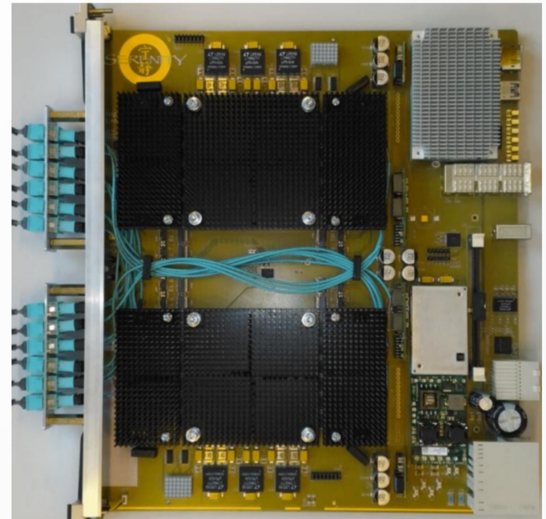
DAQ system



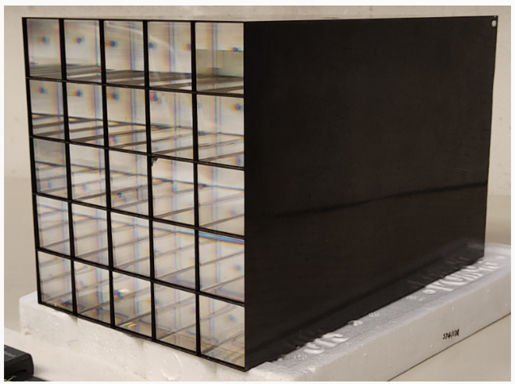
x3

~ 5Gbps/station

CMS Serenity board



ECAL

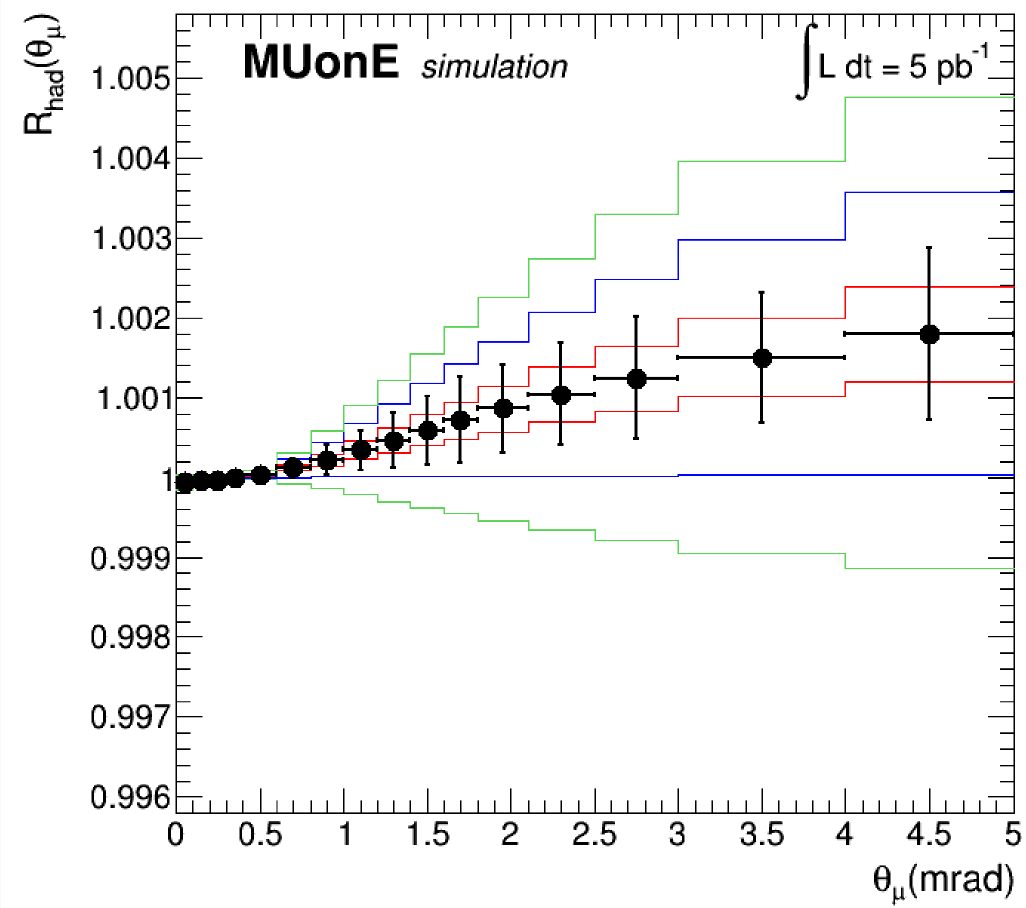


STORAGE

- Test Run: read all data with no event selection.
- Information will be used to determine online selection algorithms to be used in the Full Run.

Sensitivity to $\Delta\alpha_{had}(t)$

Expected luminosity for the Test Run: L = 5 pb^{-1} ⟷ ~10^9 events with E_e > 1 GeV (θ_e < 30 mrad)



We will be able to extract the leptonic running ($\Delta\alpha_{lep}$ ~ 10^{-2})

Initial sensitivity also to the hadronic running ($\Delta\alpha_{had}$ ~ 10^{-3})

$$K = 0.137 \pm 0.027$$

$$\Delta\alpha_{had}(t) \simeq -\frac{1}{15}Kt$$

Conclusions

- a_μ^{HLO} is the main source of uncertainty on the theoretical prediction of a_μ.
- The new method proposed by the MUonE is independent and competitive with the traditional approach.
- The CERN SPS Committee has recently approved a Test Run of 3 weeks for the MUonE experiment in Fall 2021.
- The aim of the Test Run will be to verify the detector design and evaluate the analysis strategy.
- If the Test Run will confirm the goodness of our proposal, a Run with the full detector is envisaged in 2022-24.

Thanks for your attention!

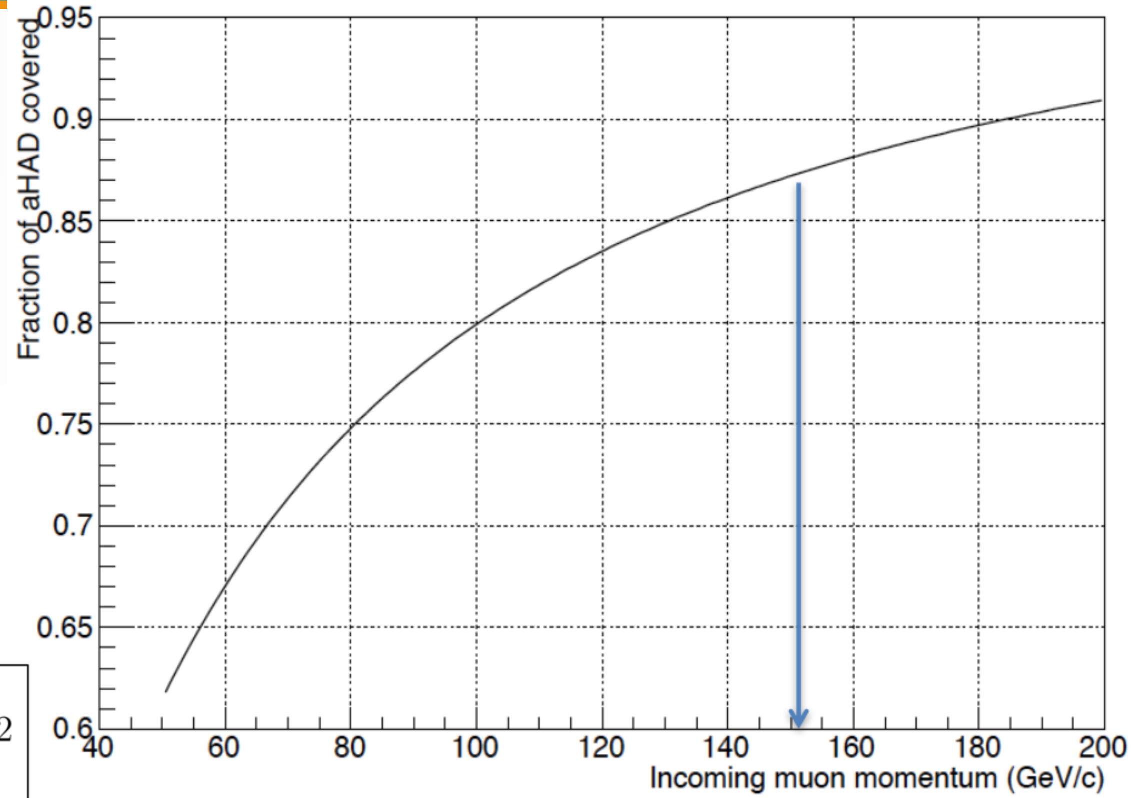
BACKUP

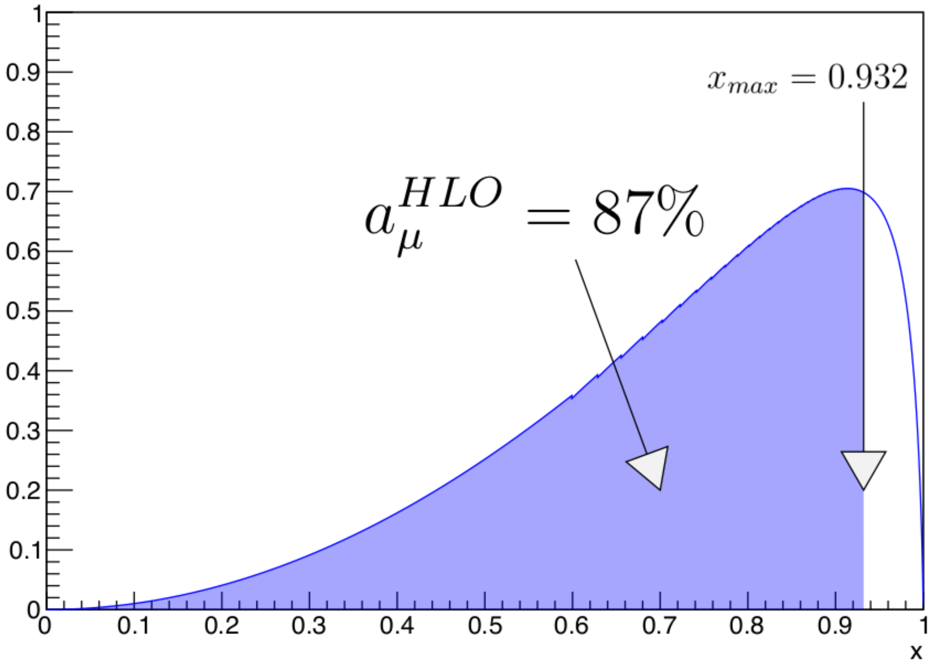
E_{beam} = 150 GeV

-0.143 GeV² < *t* < 0 GeV²

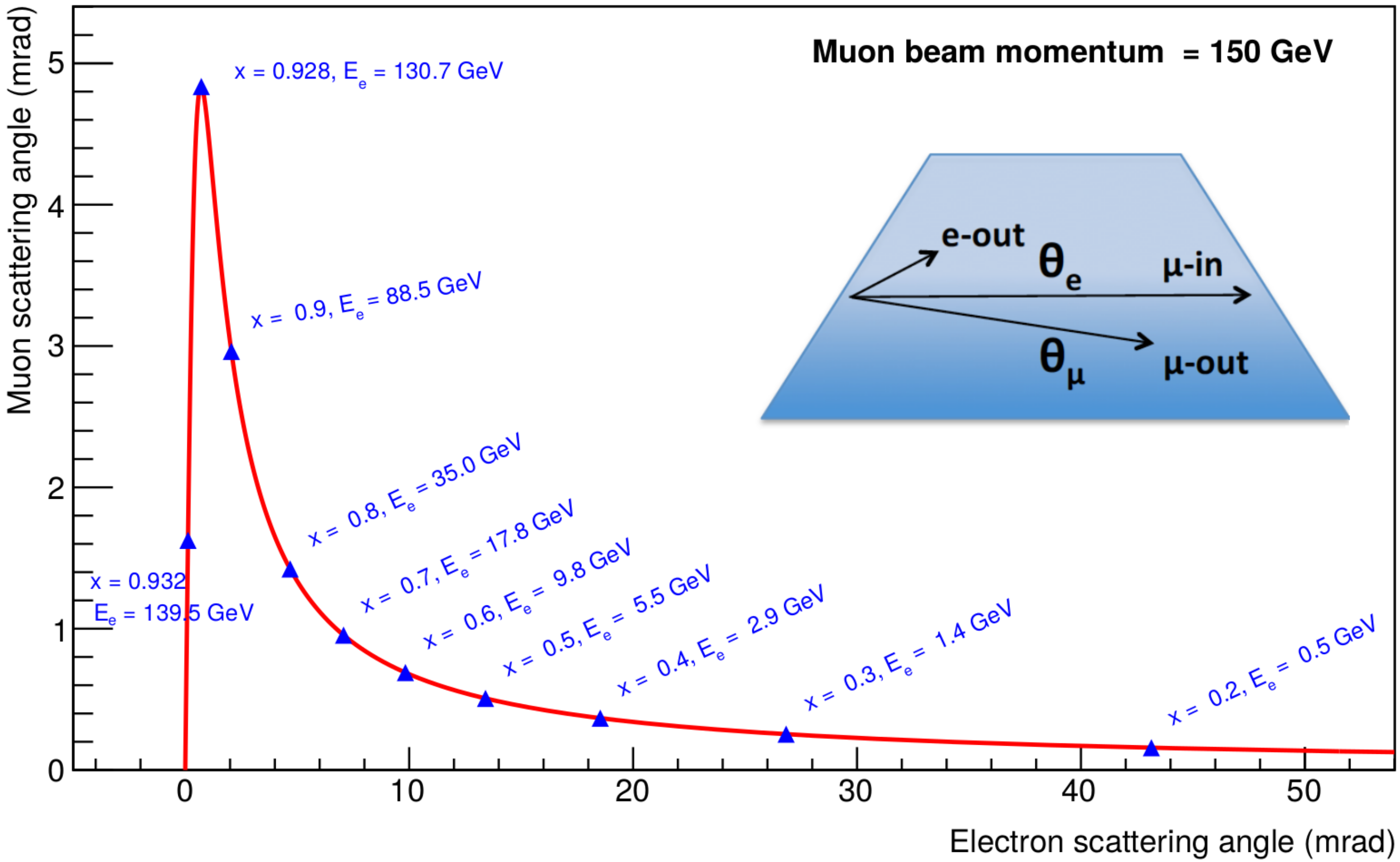
$$t(x) = \frac{x^2 m_\mu^2}{x-1} < 0$$

0 < x < 0.932





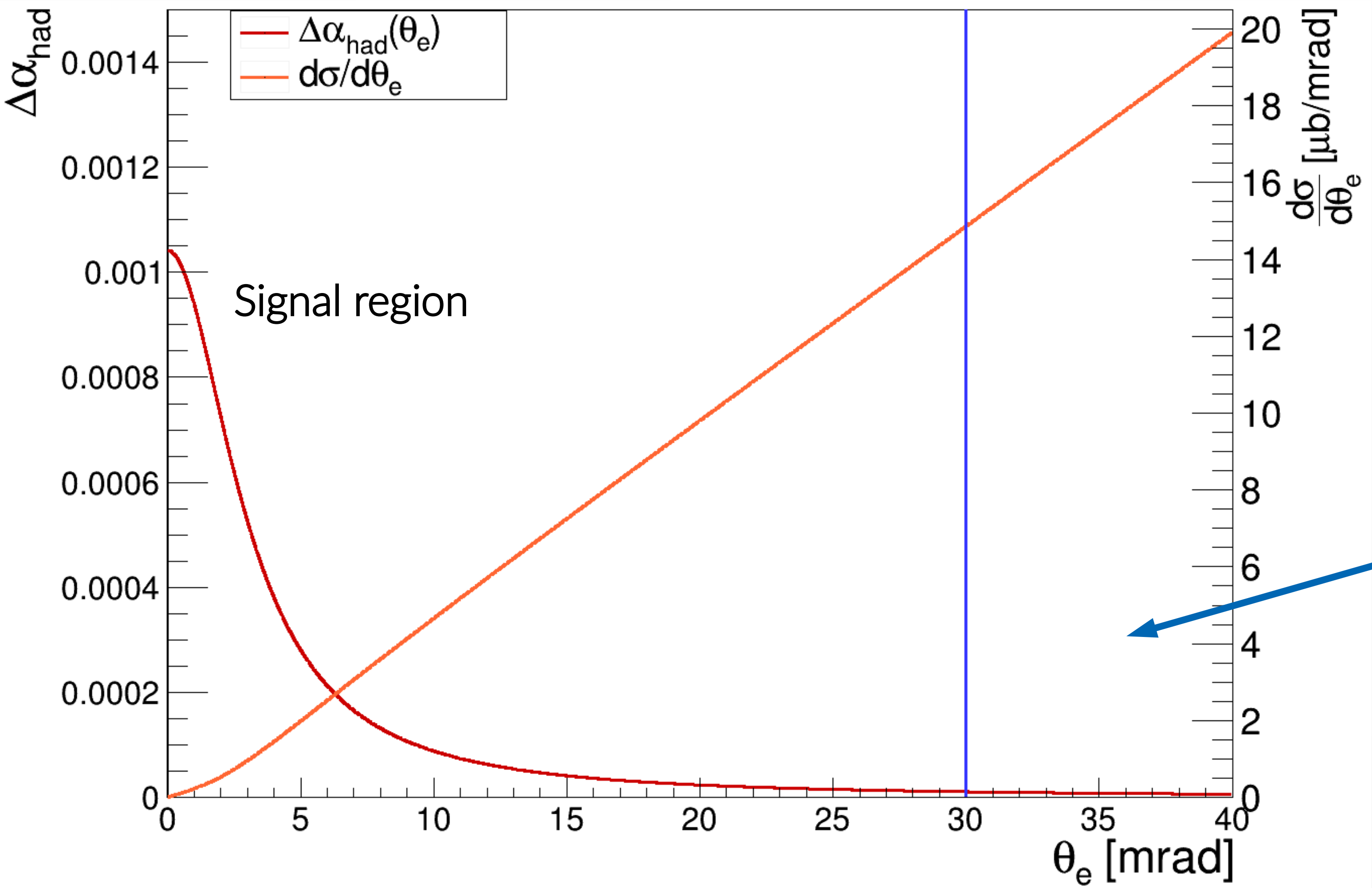
Correlation curve (θ_e, θ_μ)



It allows to select signal events and reject the background

$$\sin\theta_\mu = \frac{p'_e \sin\theta_e}{p'_\mu} = \sin\theta_e \sqrt{\frac{E_e^2(\theta_e) - m_e^2}{[E_\mu + m_e - E_e(\theta_e)]^2 - m_\mu^2}}$$

Extraction of $\Delta\alpha_{had}(t)$



$\Delta\alpha_{had}(t) \lesssim 10^{-5}$

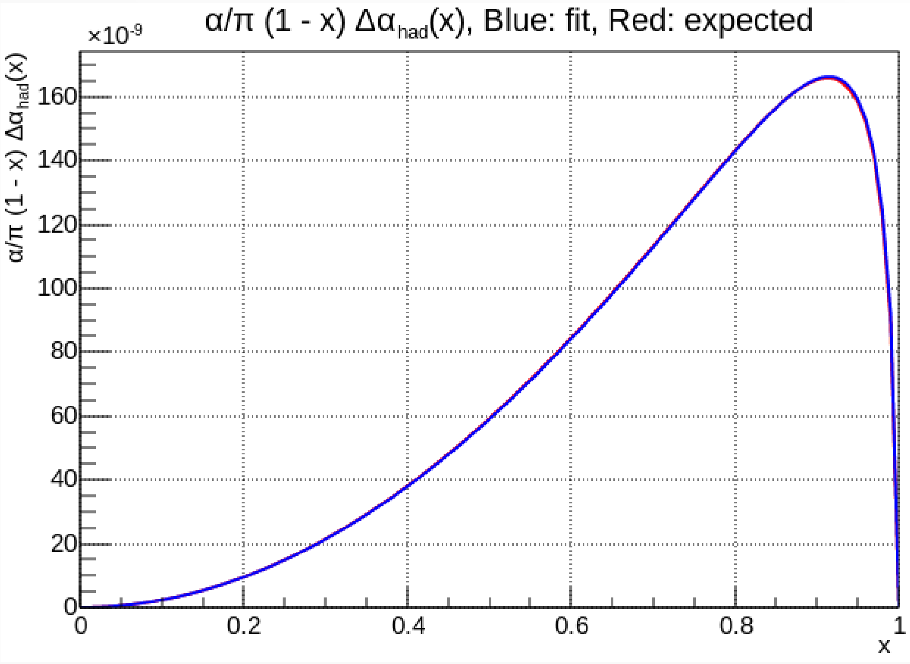
$\theta_e \gtrsim 30$ mrad

No sensitivity to $\Delta\alpha_{had}(t)$ in this region

“Lepton-like” parameterization

$$\Delta\alpha_{had}(t) = KM\left\{-\frac{5}{9} - \frac{4}{3}\frac{M}{t} + \left(\frac{4}{3}\frac{M^2}{t^2} + \frac{M}{3t} - \frac{1}{6}\right)\frac{2}{\sqrt{1-\frac{4M}{t}}}\ln\left|\frac{1-\sqrt{1-\frac{4M}{t}}}{1+\sqrt{1-\frac{4M}{t}}}\right|\right\}$$

Inspired from the analytical function of the leading order leptonic running



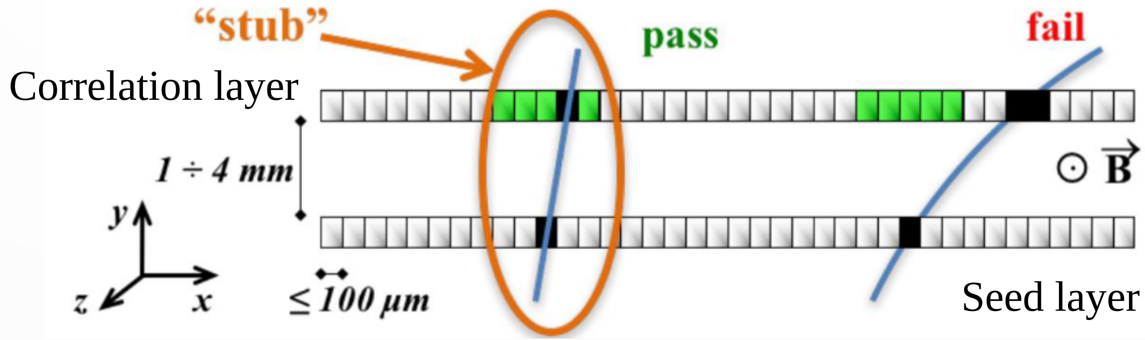
K = related to α_0 and the electric charge of the lepton in the loop (and also colour charge for quarks)

M = related to the squared mass of the particle in the loop

It allows to extrapolate $\Delta\alpha_{\rm had}(t)$ also in the region which is not accessible by kinematics (x > 0.932).

2S modules

Select only particles above a certain transverse momentum p_t for the 40 MHz readout.



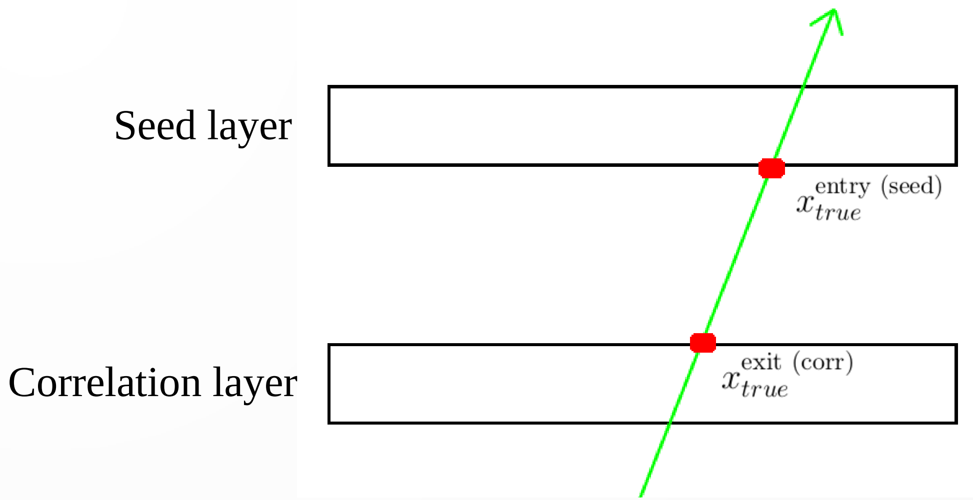
Correlation window: ±7 strips.
Window offset = 0.
Max cluster width = 4 strips.

Stub information: position of the cluster in the seed layer + distance between position of correlation cluster and seed cluster (bend)

Single hit resolution – some definitions

The single hit resolution is defined as the st.dev. of the distribution

$$x_{true} - x_{stub}$$



$$x_{true} = \frac{x_{true}^{\text{exit (corr)}} + x_{true}^{\text{entry (seed)}}}{2}$$

x_{true} = μ position in the middle of the 2S module

$x_{true}^{\text{exit (corr)}}$ and $x_{true}^{\text{entry (seed)}}$ taken from Geant4

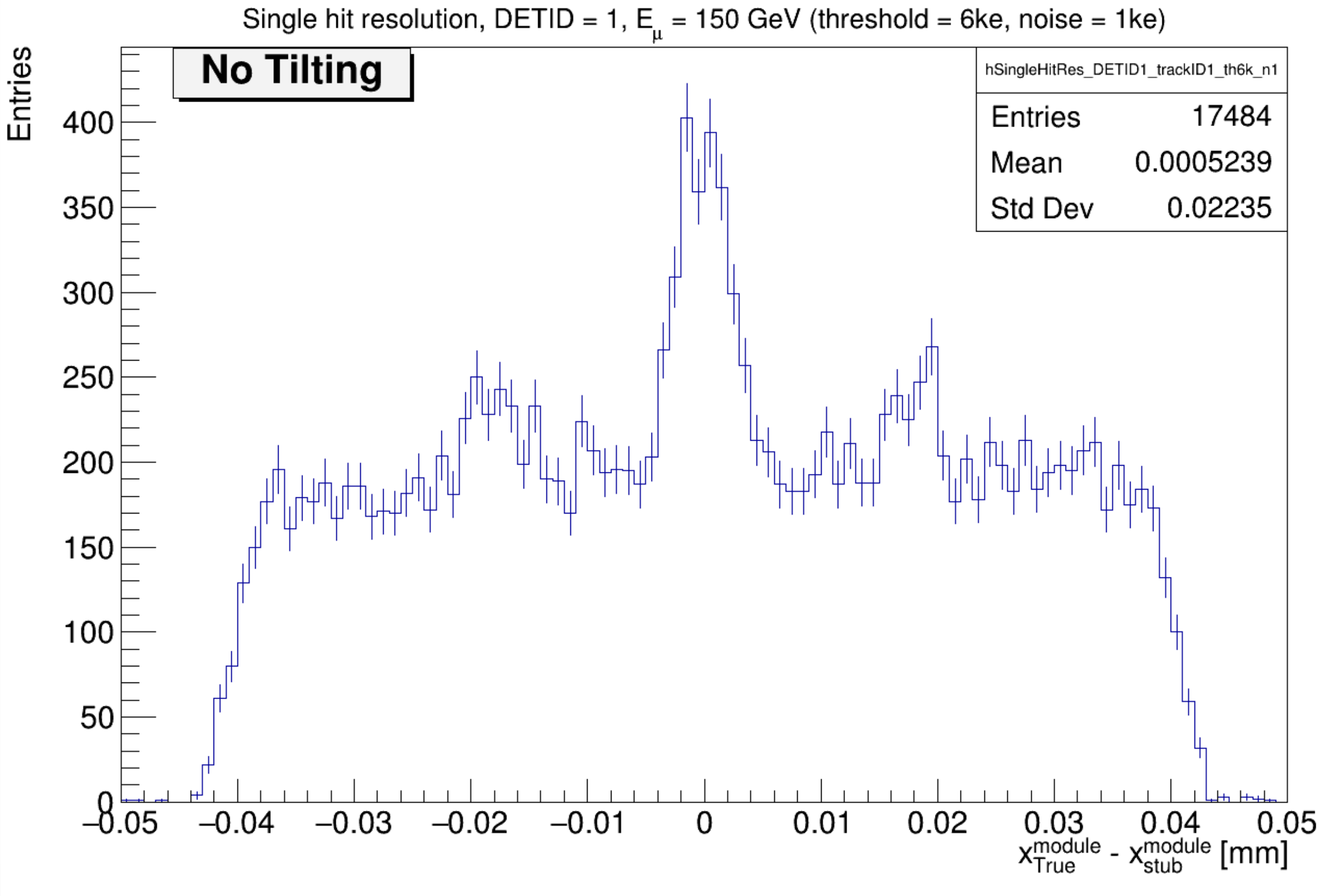
$$x_{stub} = \frac{x_{seed} + x_{corr}}{2} \qquad \text{bend} = x_{corr} - x_{seed}$$

$$x_{stub} = x_{seed} + \frac{\text{bend}}{2}$$

x_{stub} = μ position retrieved from the stub information

Single hit resolution – non tilted geometry

$$\sigma_{1hit} = 22.4\,\mu\mathrm{m}$$



Single hit resolution – tilted geometry

Tilted geometry: improvement in resolution due to two different effects:

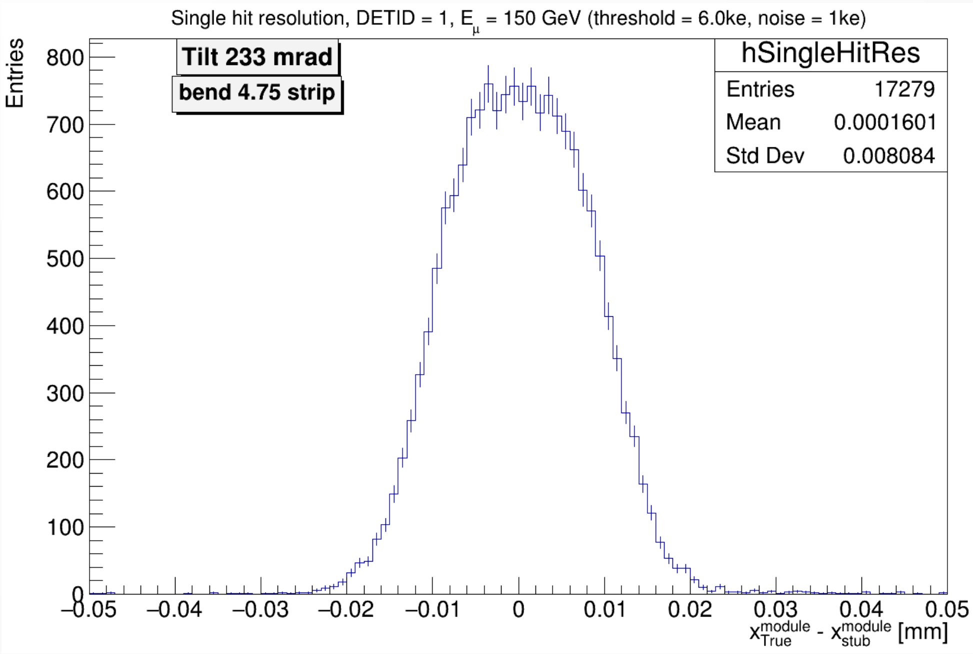
1) charge sharing: energy deposition of particles in the Si is shared among neighbouring strips

2) effective staggering: tilting a 2S module by 25 mrad is equivalent to stagger the two sensors by ½pitch

optimal point:
tilt angle: 233 mrad
threshold: 6σ

Resolution for 150 GeV muons:

$$\sigma_{1hit} = 8.0\,\mu\text{m}$$

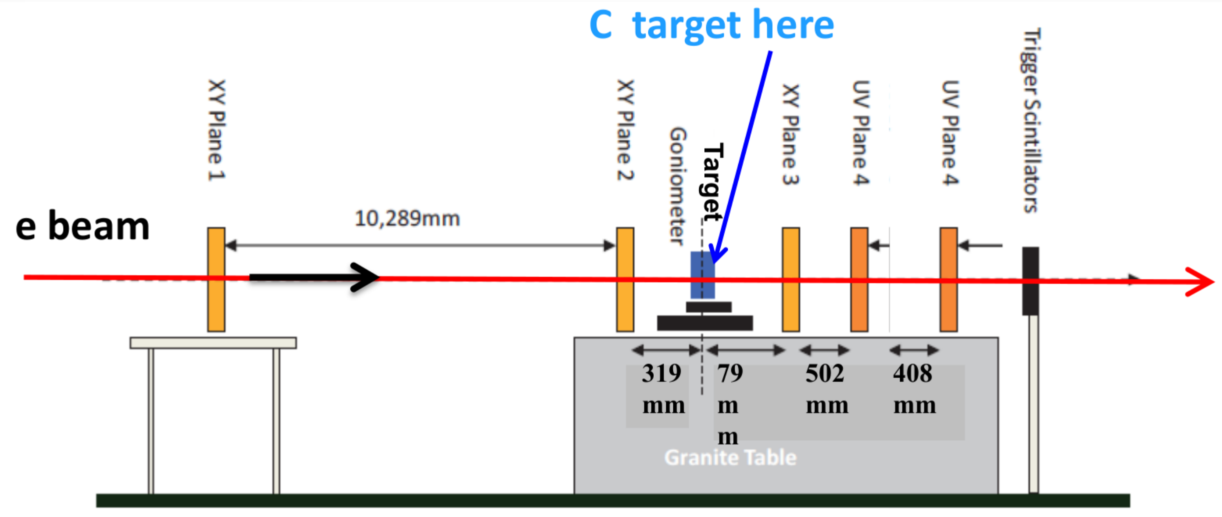


Multiple scattering: results from TB2017

Multiple scattering effects of electrons with 12 and 20 GeV on Carbon targets (8 and 20 mm)

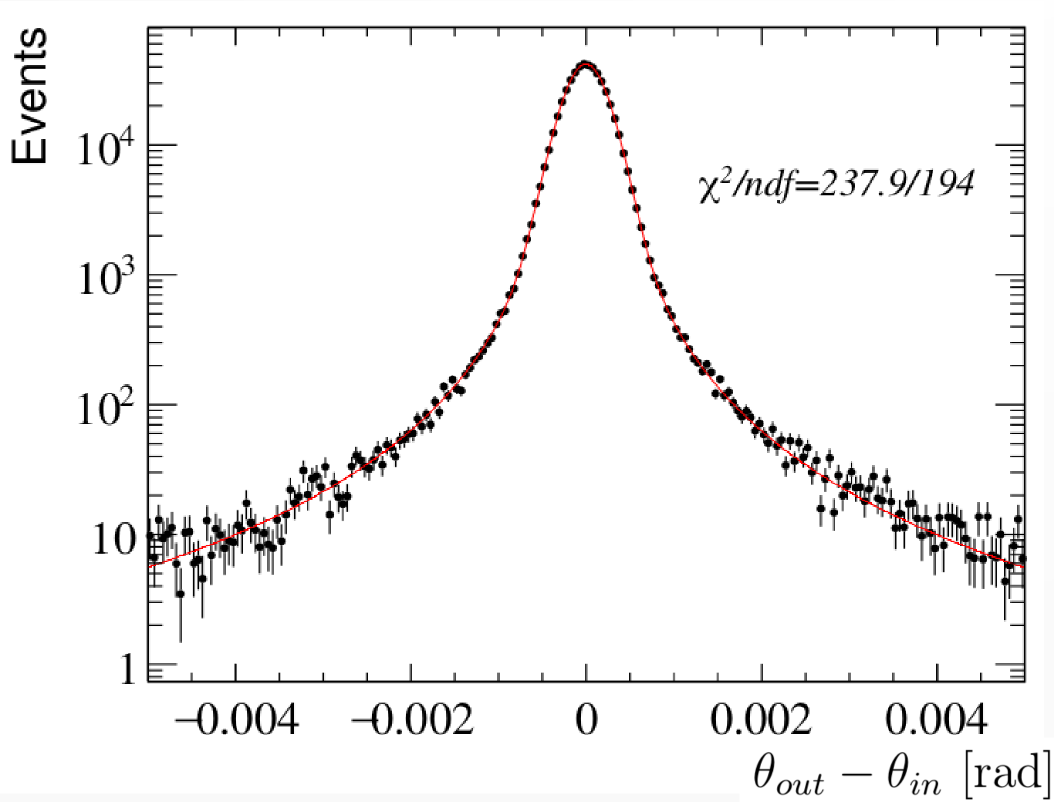
Main goals:

- to determine a parameterization able to describe also non Gaussian tails
- to compare data with a GEANT4 simulation of the apparatus



Multiple scattering: results from TB2017

$$f_e(\delta\theta_e^x) = N\left[(1-a)\frac{1}{\sqrt{2\pi}\sigma_G}e^{-\frac{(\delta\theta_e^x-\mu)^2}{2\sigma_G^2}} + a\frac{\Gamma(\frac{\nu+1}{2})}{\sqrt{\nu\pi}\sigma_T\Gamma(\frac{\nu}{2})}\left(1+\frac{(\delta\theta_e^x-\mu)^2}{\nu\sigma_T^2}\right)^{-\frac{\nu+1}{2}}\right]$$



$$\vec{p} = [N,\ a,\ \mu,\ \sigma_G,\ \nu,\ \sigma_T]$$

Results show a ~1% agreement between data and MC for the Gaussian core